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Unambiguous Double Delta Discriminator for sine-phased BOC(*n*,*n*) receiver

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Abstract

A new unambiguous discriminator similar to a conventional Double Delta correlator is tailored for sine-phased BOC(1,1) signal tracking. It is shown in this paper that it has efficient multipath mitigation at the cost of degraded noise resistance due to correlation loss of using waveform subtraction. Its multipath performances is evaluated in both coherent and dot-product type non-coherent structures. The advantage of dot-product type discriminator structure for multipath resistance is shown. Tracking code jitters are examined theoretically and empirically. A new simplified jitter expression is provided to facilitate the comparison of relative noise performance for various Strobe Correlators with the proposed discriminator, without considering the effect of bandlimiting.

Keywords: Double Delta Correlator, Ambiguity, GNSS, GPS, Multipath, Jitter, Tracking

1. Introduction

The sine-phased BOC(*n*,*n*) modulation is shared by the majority of modernised Global Navigation Satellite Systems (GNSS) and several other regional ranging systems. This advanced modulation is a multiplication of a conventional Binary Phase Shift Keying (BPSK) pseudorandom noise (PRN) code and a novel sine-phased square-wave subcarrier, both with a spreading rate of *n**1.023MHz. . In particular, sine-phased BOC (1,1) has been selected as the common baseline for both the Galileo E1 band Open Source signal and the GPS modernized L1C signals (US - EU Press 2004; Hein, Avila-Rodriguez et al. 2006; European Union. 2010). To be more precise, these signals will be Multiplexed Binary Offset Carrier (MBOC) which is even more complex than BOC(1,1) but the data channel of L1C still uses sine-phased BOC (1, 1) (Hein, Avila-Rodriguez et al. 2006). Moreover, MBOC can be approximated as a BOC(1,1) signal in a narrow front-end band (less than double-sided 12MHz) with a loss of carrier to noise ratio density (C/N0) of less than 0.6dB (Julien, Macabiau et al. 2007). Therefore the discussion in this paper focuses on the sine-phased BOC (1, 1) signal which is defined as the modulation product of the conventional non-return to zero (NRZ) PRN code (whose spreading code period is denoted as T_c = 1 chip period) and a sine-phased square-wave subcarrier with period $2T_s=T_c$, where both PRN and subcarrier have the same rate of 1.023MHz (i.e. $f_c= f_s=$ 1 x 1.023MHz).

The adoption of subcarrier results in unique Auto-correlation functions (ACF) with potentially improved noise and multipath resistance for tracking. However, side peaks on the ACF caused by subcarrier can lead to ambiguous acquisition (Yao, Lu et al.) and biased tracking (i.e. ambiguity) (Kovář, Vejražka et al. 2005). To mitigate both multipath and ambiguous tracking, several side peak cancellation techniques (Dovis 2005; Garin 2005; Nunes 2007) have been designed. Since their coherent discriminators are formed via linear combination of several correlations (Wu 2010a; Wu and Dempster 2010b; Wu and Dempster 2010c), they could be categorised as a series of correlation shaping techniques based on the concept of "Strobe Correlators" (Veitsel 1998).

Reference waveform tailoring is a process used to form a desired correlation by tailoring a series of reference waveforms. The Strobe Correlator is one of many code multipath mitigation techniques that use this process to shape its narrow and sharp discriminator function. To generate the desired tailored waveform, one can manipulate multiple time-shifted spreading waveforms by using linear or non-linear combination. Linear combination has been used in some effective correlation-based techniques such as the High Resolution Correlator (HRC or equivalent to Double Delta Correlator (ΔΔ) (Irsigler 2004)), Shaping Correlator (Garin 2005) and Gating Function (Nunes 2007), all of which utilise a "complex strobe" (Veitsel 1998) for reference waveform tailoring.

However, tracking ambiguity is not always completely removed by these techniques, since most of them fail to mitigate the existence of false stable tracking nodes on their discriminator function. In fact even though the famous "Bump-Jumping" is employed, the existence of false nodes on its discriminator function is still troublesome. It has been reported (Lin, Dafesh et al. 2003; Hollreiser 2007) that false lock events cannot be completely avoid as long as the DLL discriminator is ambiguous. Despite having the ability to reduce the threat of false tracking, the Bump-Jumping algorithm in low signal strength conditions can still suffer miss-detection or false-detection, since a false tracking decision is made based on statistical analysis of the amplitude of the secondary peaks. Having a “false node” on a DLL discriminator function for code phase tracking is risky, especially in safety of life applications.

Therefore, completely removing the tracking ambiguity, i.e. removing the false stable tracking node, leads to our motivation of this paper to introduce another new tailored waveform so that both tracking ambiguity and multipath can be mitigated. An new reference waveform tailored for sine-phased BOC(n,n) has been proposed by authors in (Wu 2011) using complex strobes resulting in a new “enhanced Double Delta Correlator”. In this paper, its effective multipath performance is compared with other existing strobe correlators in both their coherent and non-coherent discriminator structures. Its noise performance degradation as a trade-off is newly evaluated theoretically and verified empirically using numerical Monte Carlo simulations.

In section II, three existing strobe correlators as well as the proposed enhanced Double Delta (ΔΔ) using complex strobes for sine-phased BOC(1,1) are introduced. Their multipath performances are compared in section III. The code jitters are evaluated theoretically in section IV, where numerical Monte Carlo simulations are used for verification. Finally, concluding remarks are given in section V.

2. Correlation-Based Multipath Mitigation Techniques for Ambiguity Mitigation

In Figure 1, key reference waveforms using complex strobes tailored for sine-phased BOC(1,1) are shown along with the corresponding GNSS spreading waveforms. We define here that a strobe pulse is a symmetrical function normalised by T_c with non-zero values in the duration of gate width D (<0.5chip).

For those using complex strobes, the “W1-pulse” “W2-pulse” and the “Center pulse” are three basic waveforms commonly selected for the shaping of symmetrical Strobe Correlators, referring to Figure 1**Error! Reference source not found.**. Their mathematical expressions and derivations have been provided in authors’ previous publications (Wu 2008; Wu 2010a; Wu and Dempster 2010b). The “W1-pulse” has strobe pulses only symmetrically aligned to the bit-phase transitions occurring at the spreading waveform boundaries (at multiple integers of 1chp) (Nunes 2007); while the “W2-pulse” aligned to all the spreading symbol boundaries, regardless of the existance of bit-phase transitions (Nunes 2007). The “Centre-pulse” is unique for sine-phased BOC(1,1) and synchronizes to all the bit-phase transitions occurring at the spreading symbol centres (at multiple odd integers of 0.5chip) (Garin 2005; Wu 2008; Wu 2011).

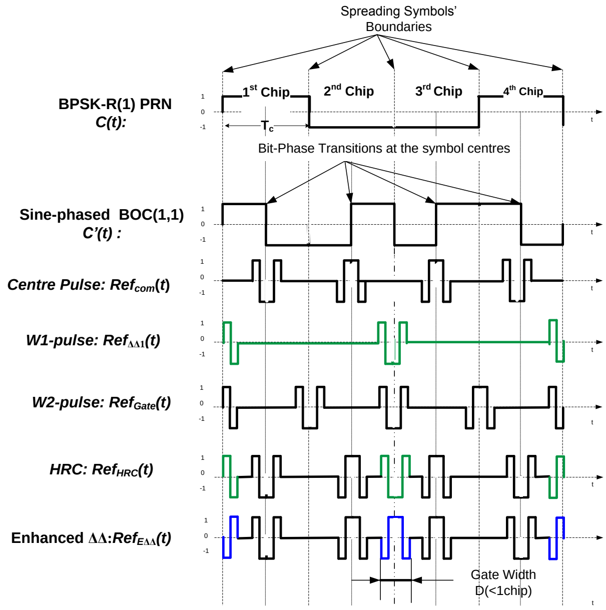

Figure 1: Examples of the relative placement of the complex strobe pulses on the reference waveforms tailored for sine- phased BOC(1,1) with strobe pulse gate width D<0.5chip

2.1 Discriminator Structures

The Strobe Correlators can be implemented in both coherent and non-coherent discriminator structures. In this paper, a non-coherent discriminator refers to a dot-product type discriminator where a coherent discriminator ($D_{co}(\tau)$) can be the generated through:

$$D_{co}(\tau) = S(t) \otimes Ref(t+\tau) \quad (1)$$

where S(t) is the received GNSS signal and the $Ref(t+\tau)$ is the tailored reference waveform with arbitrary delay τ in chips. The corresponding dot-product non-coherent discriminator function ($D_{DP}(\tau)$) is the dot-product of $D_{co}(\tau)$ and an ACF of the spreading waveform (e.g. sine-phased BOC(1,1) waveform) :

$$D_{DP}(\tau) = I_{BP}(\tau) I_{BB}(\tau) + Q_{BP}(\tau) Q_{BB}(\tau) \quad (2)$$

where I_{BP} and Q_{BP} are the in-phase and out-phase components of a $D_{co}(\tau)$ respectively. The $I_{BB}(\tau)$ and the $Q_{BB}(\tau)$ are the in-phase and out-phase prompt correlators representing the ACF. In this paper a dot-product type discriminator function is normalized as:

$$\bar{D}_{DP}(\tau)|_{\tau\to 0} = \frac{I_{BP}(\tau)I_{BB}(\tau)+Q_{BP}(\tau)Q_{BB}(\tau)}{\sqrt{I_{BB}(\tau)^2+Q_{BB}(\tau)^2}} \quad (3)$$

2.2 Existing Strobe Correlators using Complex Strobes

Three complex strobes effectively designed for sine-phased BOC(*n*,*n*) using the "W1-pulse" "W2-pulse" and the "Center pulse" are introduced in this subsection.

***A.** HRC Correlator*

The HRC is a conventional Strobe Correlator which can be produced by (Braasch 2001):

$$D_{co}^{HRC}(\tau) = 2 * R(\tau/2) - R(\tau) \quad (4)$$

where the $R(\tau)$ is a Early-minus-Late correlator:

$$R(D) = \frac{1}{2}(R_{ACF}(t-\frac{D}{2}) - R_{ACF}(t+\frac{D}{2})) \quad (5)$$

generated by subtracting two time-shifted BOC(n,n) Auto-Correlation Functions ($R_{ACF}(t)$).

Alternatively, taking the concept of Strobe Correlator given in (1), the HRC correlator can be re-produced by using a tailored reference waveform ($Ref_{HRC}(t)$) shown in Figure 1, which is sensitive to all the transitions on the GNSS spreading waveform. Hence, the tailored reference waveform can be realised as an addition of W1-pulse and Centre-pulse waveforms. Performance studies of the HRC correlator for conventional GPS BPSK signals are not new (McGraw 1999; Braasch 2001; Jones 2004; Liu and Amin 2009); however studies of its application to BOC signals are very few. The multipath performance of its coherent discriminator structure was discussed in (Irsigler 2003). However the tracking performance, especially the code tracking variance of its dot-product type discriminator structure for sine-phased BOC(1,1) has not yet been fully evaluated and compared with similar Strobe Correlators in open literature.

Applying the discriminator structures expressed in (1)(2)(3) to HRC, the normalized HRC coherent $\bar{D}_{co}^{HRC}(\tau)$ and non-coherent discriminators $D_{DP}^{HRC}(\tau)$ with D=0.1chip are shown in Figure 2. The HRC discriminator function is ambiguous since there are two false tracking nodes (with positive gains) at +/-0.5chip on the $\bar{D}_{DP}^{HRC}(\tau)$.

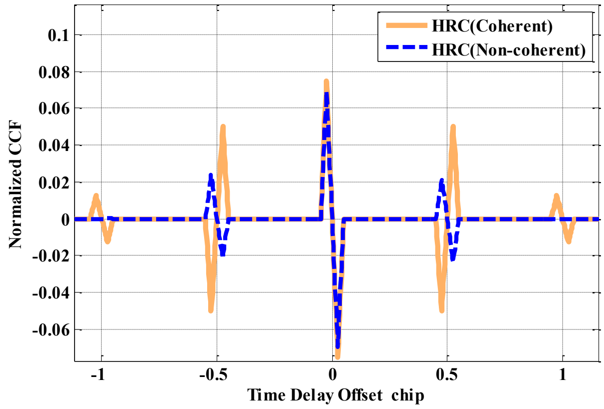

Figure 2: Normalized coherent and dot-product type non-coherent HRC discriminator functions using complex strobes. D=0.1chip, infinite pre-correlation bandwidth.

***B.** Gating Function*

The Gating Function (Nunes 2007) uses a W2-pulse for both multipath and ambiguity cancelation. The W2-pulse is more sensitive to noise power than the W1-pulse for BPSK signal tracking (Veitsel 1998) and sine-phased BOC(1,1) signal tracking (Wu and Dempster 2010b). It has good multipath mitigation since its strobe pulses are aligned to the PRN spreading symbol boundaries (Veitsel 1998; Wu 2010a; Wu and Dempster 2010b). With the implementation of the Gating Function, in a DLL the number of false tracking nodes is reduced; however there is still one remains at +0.5chip on its discriminator function as shown in Figure 3.

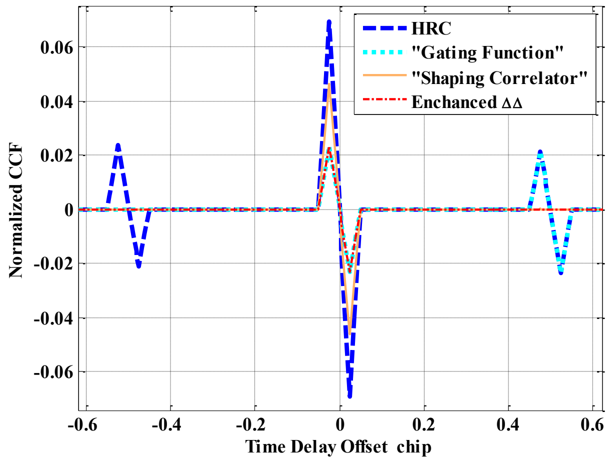

Figure 3: Normalized dot-product type non-coherent discriminator functions of Strobe Correlators using complex strobes. D=0.1chip, infinite pre-correlation bandwidth.

***C.** Shaping Correlator*

The unique "Centre-pulse" waveform ($Ref_{com}(t)$) is utilised in the Shaping Correlator for the formulation of a basic coherent correlation function $D_{com}(\tau)$. The zero-crossings on both sides of the $D_{com}(\tau)$ in the range of (-1

1) chip, can be cancelled by linearly combining three time-shifted correlators $D_{com}(\tau)$ as:

$$\bar{D}_{co}^{Shap}(\tau) = \bar{D}_{com}(\tau) - \bar{D}_{com}(\tau-1) - \bar{D}_{com}(\tau+1) \quad (6)$$

From (6), it is clearly shown that unlike aforementioned techniques, the coherent Shaping Correlator discriminator $\bar{D}_{co}^{Shap}(\tau)$ is a product of three independent correlators as they are separated by up to 1chip (Van Dierendonck 1992). It has been shown in (Wu 2010a; Wu and Dempster 2010c) that this separation leads to its noise performance degradation. Since this discriminator function $\bar{D}_{co}^{Shap}(\tau)$ has two other stable tracking nodes beyond the range of (-1 1) chip as admitted and shown by inventor in (Garin 2005), its coherent discriminator is still an ambiguous solution, despite its non-coherent version being unambiguous, as shown in Figure 3.

2.3. Enhanced Double Delta Correlator

To completely remove the ambiguity, both a W1-pulse and a Centre-pulse are used to tailor the novel reference waveform for sine-phased BOC(1,1). However, unlike the waveform of HRC ($Ref_{HRC}(t)$) , in the proposed waveform $Ref_{E\Delta\Delta}(t)$ portrayed Figure 1, the W1-pulse is subtracted from rather than added to the Centre-pulse. Alternatively, the enhanced ΔΔ can be generated based on the tailored waveform of the HRC and Centre-pulse as:

$$\bar{D}_{co}^{E\Delta\Delta}(\tau) = 2*\bar{D}_{com}(\tau) - \bar{D}_{co}^{HRC}(\tau) \quad (7)$$

That subtraction in (7), plays a role in reshaping the discriminator function by sacrificing the contribution of phase energy at the edge of spreading symbols. The resulting coherent CCF $\bar{D}_{co}^{E\Delta\Delta}(\tau)$ looks identical to the conventional ΔΔ for BPSK signal (Wu 2008). This new unambiguous discriminator function with D=0.1chip is portrayed in Figure 3. It can be observed that, the discriminator function patterns of various Strobe Correlators using complex strobes are similar around τ=0chip, which explains their similar multipath performance (Braasch 2001). Regarding noise performance, the discriminator gains around τ=0chip vary corresponding to their different sensitivity to the desired signal. However, the code tracking jitter also results from the received noise power involved in the correlation process (in Eq.(1), where the additive independent noise is not shown but included in $S(t)$).

3. Multipath Performance

To evaluate the multipath effect on the correlation based techniques, a simplified two-path signal model is used (Van Dierendonck 1996; Fante). The reflected signal is assumed to have half the signal amplitude of the direct one (i.e. α =0.5) with 0 and π relative carrier phase differences, so that the maximum multipath error envelope (MA) (Irsigler 2005) as well as its average running area (ARA) (Irsigler 2005) can be obtained assuming infinite bandwidth. Complying with the parameter selection in (Garin 2005) (Nunes 2007), a strobe gate width D=0.1chip is used in this paper for multipath performance analysis.

3.1 On Coherent Discriminator

The MA are estimated for coherent discriminators with D=0.1chips shown in Figure 4. The performance of the coherent Shaping correlator is not portrayed here, since it is not an unambiguous solution. As can be observed from Figure 4, the Gating Function is the best among the three coherent discriminators. The enhanced ΔΔ has better medium delay multipath mitigation compared to HRC.

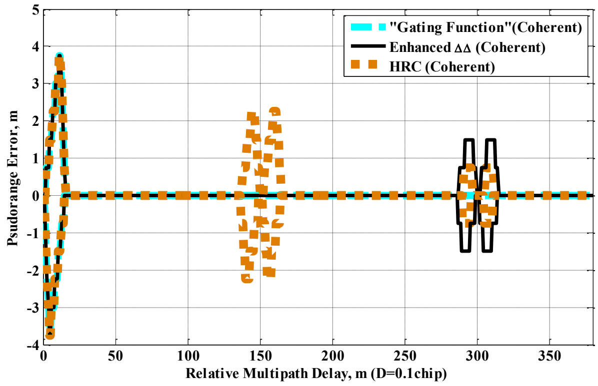

Figure 4: Multipath Error Envelop of various coherent "Strobe Correlators", with D=0.1 chip, assuming infinite bandwidth

3.2 On Non-coherent Discriminator

Since the proposed enhanced ΔΔ for sine-phased BOC(1,1) has a discriminator function similar to the conventional HRC for the corresponding BPSK waveform, as expected, they both experience similar multipath mitigation performance regardless of the selection of gate width D or the front-end band-limiting effect which has been extensively discussed (McGraw 1999; Liu and Amin 2005; Liu and Amin 2009). However, on the other hand, the conventional HRC for sine-phased BOC(1,1) is unable to eliminate the medium-delay multipath tracking error unless techniques such as the "Shaping Correlator" (Garin 2005) or "Gating Function" (Nunes 2007) are implemented. In contrast, the proposed enhanced ΔΔ for sine-phased BOC(1,1) successfully preserves the multipath performance of conventional HRC by eliminating the medium-delay multipath tracking error, despite the fact that it does not have a novel discriminator function pattern.

Since all of the discussed Strobe Correlators use complex strobe pulses, they all have similar sharp and narrow discriminator functions especially in a dot-product type non-coherent discriminator structure. All the Strobe Correlators including the proposed enhanced ΔΔ, therefore achieve similar closed-space multipath mitigation as shown by the MA and ARA performance given in Figure 5 and Figure 6 respectively.

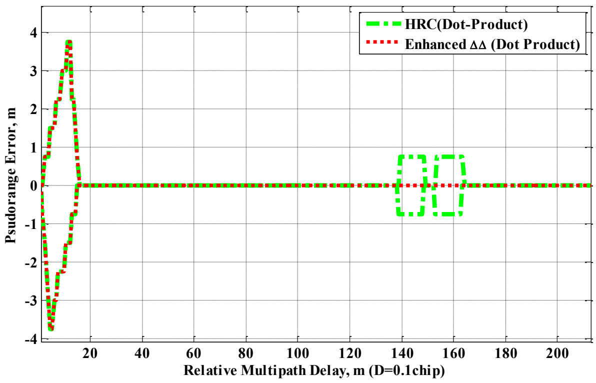

Figure 5: Multipath Error Envelop (MA performances) of dot-product type non-coherent HRC VS. enhanced ΔΔ , with D=0.1 chip, assuming infinite bandwidth

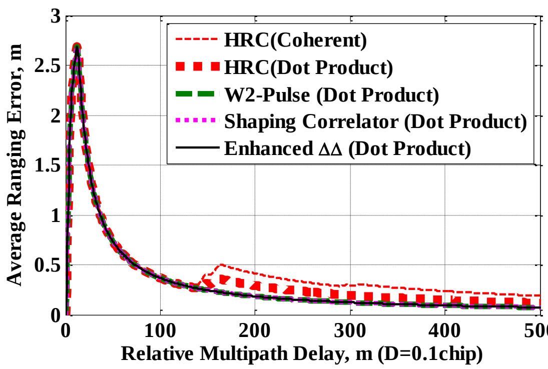

Figure 6: ARA performances for "Strobe Correlators" implemented in dot-product type non-coherent discriminator structure, with D=0.1 chip, assuming infinite bandwidth

It is worth pointing out that the coherent and non-coherent discriminator structures play different roles in multipath resistance (by comparing Figure 4 and Figure 5). The improvement is achieved thanks to the dot-product multiplication (refer to Eq. (2)) where less weight is given to the coherent discriminator function with time delay τ close to the value of a spreading symbol period T_c or the edge of each spreading symbol. Due to this difference, the "Shaping Correlator" becomes an unambiguous discriminator in the dot-product type non-coherent discriminator structure (Garin 2005).

The advantage of the enhanced ΔΔ over the HRC can be observed from the MA and ARA performances for sine-phased BOC(1,1) shown in Figure 4 and Figure 6 respectively. Observing Figure 6, one can notice that the tracking error around 300m (i.e. the propagation distance of the GNSS radio signal in duration of T_c.), is significantly improved compared to the results for coherent discriminator structures given in Figure 4. Moreover, the enhanced ΔΔ performs equivalently well as the "Shaping Correlator" or "Gating Function" in terms of multipath mitigation. In Figure 6, the other non-coherent discriminators, including those shown in Figure 3, achieve the same improved resistance to medium-long delay multipath as that of the enhanced ΔΔ and their results are not shown here to avoid overlapping.

4. Noise Performances

It was theoretically proven in (Wu 2010a; Wu and Dempster 2010c) that the white Gaussian noise resistance of the Strobe Correlators can be evaluated via hypothesis. It was pointed out in (Wu 2010a) that Strobe Correlators can also be compared intuitively using a simplified jitter expression :

$$\sigma^2_{strobe,\varepsilon_\tau} = \left\{ \frac{B_L(1-0.5B_L T_I)\varpi}{\frac{C}{N_0}k^2} \left(1 + \frac{1}{\frac{C}{N_0}T_I \Lambda} \right) \right\} \quad (8)$$

where k is the discriminator gain; Λ is the power of the received GNSS spreading waveform; ϖ is the power of the tailored reference waveform; B_L, T_I and C/No are the single-sided loop bandwidth, integration time and output Carrier-to-Noise ratio respectively. This simplified jitter expression is valid when the same code tracking structure described by Eq.(2) is used with the same local replica for prompt correlators. If a complex strobe is used for all the tailored reference waveforms, similar trends of sensitivity to pre-correlation filtering can be expected (Wu 2010a; Wu and Dempster 2010c). Then the relative code jitters of the discussed Strobe Correlators can be approximated without considering the effect of band-limiting.

The approximate relative code jitters are compared in Table 1, where the power of the BPSK spreading waveform without tailoring is normalized as "1". Similarly, the power of a tailored waveform for BPSK is D. Since the probability of occurrence of bit-phase transitions on a PRN waveform is 50%, the power of a W1-pulse is ½ D. This power is directly related to the received noise power. In (1), the locally generated reference correlates with the received signal, where the power of the received noise has also been "tailored". On the other hand, the normalized discriminator gain for BPSK tracking is normalized to be "1". The discriminator gains indicating the sensitivity to the desired signal is directly related to the number of strobe pulses aligned to transitions on a GNSS spreading waveform.

Table 1: Intuitive relative Code jitter of "Strobe Correlators" using complex strobe, gate width D (<0.5chip), without considering the pre-correlation filtering

Discriminator	**Gain (Slope) *k***	**Power of the Strobe Pulse Waveform ϖ**	**Relative Code Jitter $\sigma^2_{strobe,\varepsilon_\tau}$**
For BPSK-R(1)			
HRC	**1**	$\frac{1}{2}\cdot D$	$\frac{1}{2}\cdot D$
For sine-phased BOC(1,1)			
HRC	**3**	$\frac{3}{2}\cdot D$	$\frac{1}{6}\cdot D$
Gating Function	**1**	D	D
Shaping Correlator	**2**	3D	$\frac{3}{4}\cdot D$
"Enhanced ΔΔ"	**1**	$\frac{3}{2}\cdot D$	$\frac{3}{2}\cdot D$

*Note that, the "Shaping correlator" has 3 times higher noise power than "Gating Function" since it is a combination of three independent correlators with time delay separation of 1chip

To verify the intuitive performance comparison, numerical Monte Carlo simulations are carried out. The Code jitter errors are estimated based on an experimental approach (Van Dierendonck 1992; Van Dierendonck 1996; Wu 2010a). The measured code tracking error variance is calculated according to one-sigma tracking loop noise performance (Van Dierendonck 1992; Van Dierendonck 1996):

$$\tilde{a} = \frac{\sqrt{2B_L T_I}}{G_d}\sigma_{d_\tau} \qquad (9)$$

where σ_{d_τ} is the measured standard deviation (STD) of the discriminator output before smoothing, B_L is the single-sided loop bandwidth in Hz and G_d is the discriminator gain obtained after proper normalisation (i.e. total signal power) according to Eq. (3).

The measured code tracking variance estimations shown in Figure 7 are obtained from a DLL using a code loop bandwidth B_L=1Hz, integration time T_I=0.008s and a wide pre-correlation filter approximated by a 7th order low-pass Butterworth with double-sided bandwidth 2*B*=14.9504MHz. and a gate width *D*=1/3chip for the GIOVE-A E1(OS) pilot Channel. Such a wide front-end bandwidth is used so that it complies with the bandwidth requirement of 2*B*>4*1.023/*D* for Strobe Correlators using symmetrical complex strobe pulses for sine-phased BOC(1,1) tracking (Wu 2010a; Wu and Dempster 2010c). In total, 35000 independent estimations were obtained in the Monte Carlo tests. The trends of the estimated jitters shown in Figure 7 verified the approximate comparison listed in Table1.The proposed enhanced ΔΔ suffers from the highest tracking error due to loss of sensitivity to desired signal. In fact, the discussed ambiguity cancelation techniques, e.g. the "Gating Function", the "Shaping Correlator" and the "Enhanced ΔΔ", more or less suffer some degradation in noise performance, although they can achieve good medium-long delay multipath mitigation compared to the HRC.

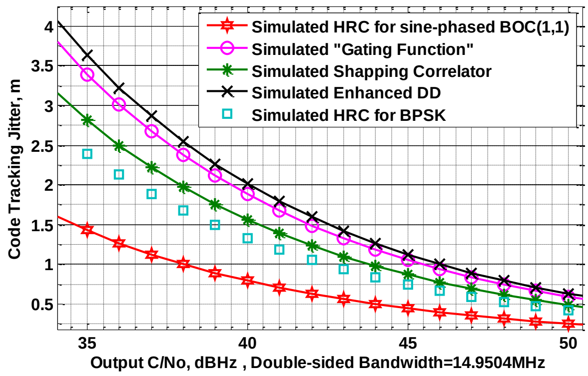

Figure 7: Code tracking error comparisons among "Strobe Correlators" for the sine-phased BOC(1,1). (with D= 1/3chip , front-end bandwidth 14.95MHz, B_L=1Hz, T_I=8ms)

5. Conclusion

The Enhanced Double Delta correlator is an unambiguous Strobe Correlator tailored for sine-phased BOC(1,1) signal tracking using both coherent and dot-product type non-coherent structures. It is shown to preserve the advantages of the conventional HRC for GPS BPSK signal while successfully improving medium-delay multipath error. It achieves equivalent multipath mitigation to the "Shaping Correlator" and "Gating Function" at the cost of degraded noise resistance. Dot product type non-coherent structures can result in better multipath resistance. Relative Code jitter performance can be evaluated using an intuitive approach verified with numerical Monte Carlo simulations if in a scenario where the pre-correlation filtering effect is less significant for performance comparison.

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Reference

Braasch, M. S. (2001). *Performance Comparison of Multipath Mitigating Receiver Architectures*. Aerospace Conference IEEE Proceedings, 2001,. Vol. 3: 1309-1315.

Dovis, F., Mulassano, P., Lo Presti, L. (2005). *A Novel Algorithm for the Code Tracking of BOC(n,n) Modulated Signals*. ION GNSS 18th International Technical Meeting of the Satellite Division of the U.S. Institute of Navigation, Long Bench, California. September 13-16: 152—155.

European Union. (2010). *Galileo OS SIS ICD (Open Service Signal-In-Space Interface Control)* [Access online] in from.http://ec.europa.eu/enterprise/policies/satnav/galileo/open-service/index_en.htm

Fante, R. (2003). *Unambiguous Tracker for GPS Binary-Offset Carrier Signals*. Proceedings of the 59th ION National Technical Meeting, Albuquerque, New Mexico. June 23-25: 141-145.

Garin, L. (2005). *The" Shaping Correlator", Novel Multipath Mitigation Technique Applicable to Galileo BOC (1, 1) Modulation Waveforms in High Volume Markets*. Conference Proceeding of ENC-GNSS, Munich, Germany. July 19 - 22

Hein, G. W., J. Avila-Rodriguez, et al. (2006). *MBOC: The New Optimized Spreading Modulation Recommended for Galileo L1 OS and GPS L1C*. Position, Location, and Navigation Symposium, IEEE/ION PLANS, San Diego, California. April 25-27: 883- 892.

Hollreiser, M., et al., (2007). *Galileo Signal Experimentation*. GPS World: 37-44 [Access online] in

Irsigler, M., Avila-Rodriguez, J.A., Hein, G.W. (2005). *Criteria for GNSS Multipath Performance Assessment*. Proceedings of the 18th International Technical Meeting of the Satellite Division of the Institute of Navigation, ION GNSS 2005, Long Beach, California. September 13-16

Irsigler, M., Eissfeller, B. (2003). *Comparison of Multipath Mitigation Techniques with Consideration of Future Signal Structures*. International Technical Meeting of the Satellite Division of the Institute of Navigation, ION GPS/GNSS 2003, Oregon, Portland. September 9-12: 2584 - 2592.

Irsigler, M., Hein,G.W., Eissfeller, B. (2004). *Multipath Performance Analysis for Future GNSS Signals*. Proceedings of the National Technical Meeting of the Satellite Division of the Institute of Navigation, ION NTM, San Diego, California. January 26-28

Jones, J., Fenton, P., Smith, B (2004). *Theory and performance of the pulse aperture correlator*. NovAtel Inc. 9 [Access online] in from.http://www.novatel.com/Documents/Papers/PAC.pdf

Julien, O., C. Macabiau, et al. (2007). *On Potential CBOC/TMBOC Common Receiver Architectures*. Proceedings of the 20th International Technical Meeting of the Satellite Division of the Institute of Navigation ION GNSS 2007, Fort Worth, Texas. 1530 - 1542.

Kovář, P., F. Vejražka, et al. (2005). "*Galileo Receiver Core Technologies*." Journal of Global Positioning Systems 4(1-2): 176-183.

Lin, V., P. Dafesh, et al. (2003). *Study of the Impact of False Lock Points in Subcarrier Modulated Ranging Signals and Recommended Mitigation Approaches*. Proceedings of the ION 59th Annual Meeting and CIGTF 22nd Guidance Test Symposium, Albuquerque, New Mexico. June 23 - 25: 156-165.

Liu, L. and M. Amin (2005). *Multipath and Precorrelation Filtering Effect on GPS Noncoherent Early-Minus-Late Power Discriminators*. Proceedings of the Fifth IEEE International Symposium on Signal Processing and Information Technology, 2005. , Athens. 21-21 Dec: 417 - 422

Liu, L. and M. Amin (2009). "*Tracking performance and average error analysis of GPS discriminators in multipath*." Signal Processing 89(6): 1224-1239.

McGraw, G. A., Braasch, M.S. (1999). *GNSS Multipath Mitigation Using Gated and High Resolution Correlator Concepts*. Proceedings of the 1999 National Technical Meeting of the Institute of Navigation, San Diego, California. January 25 - 27: 333-342.

Nunes, F. D., Sousa, F.M.G., Leitão, J.M.N. (2007). "*Gating Functions for Multipath Mitigation in GNSS BOC Signals*." IEEE Transactions on Aerospace and Electronic Systems 43(3): 951-964.

US - EU Press (2004). *Agreement on the Promotion, Provision and Use of GALILEO and GPS Satellite-Based Navigation Systems and Related Applications* [Access online] in September, 7, 2009 from.http://www.official-documents.gov.uk/document/cm73/7384/7384.pdf

Van Dierendonck, A. J. (1996). *GPS Receivers*. Global Positioning System: Theory and Applications. B. Parkinson, J. Spilker, A. Editors, P. Alelrad and P. Enge. 1: 329-407.

Van Dierendonck, A. J., Fenton, P., Ford, T. (1992). "*Theory and Performance of Narrow Correlator Spacing in a GPS Receiver*." Navigation: Journal of Institute of Navigation 39(3): 265-283.

Veitsel, V., Zhdanov, A., Zhodzicshky, M. (1998). "*The Mitigation of Multipath Errors by Strobe Correlators in GPS/GLONASS Receiver*." GPS Solutions 2(2): 38-45.

Wu, J. (2010a). *Binary Offset Carrier (BOC) Receiver Design*. School of Surveying and Spatial Information Systems, Faculty of Engineering (PhD Thesis). Sydney, Univeristy of New South Wales. Doctor of Philosophy [Access online] in from.http://unsworks.unsw.edu.au/vital/access/manager/Repository/unsworks:8750

Wu, J. and A. G. Dempster (2010b). "*Strobe Correlators" using "W2-pulses"*." Signal Processing, Volume 92, Issue 5, May 2012, ISSN 0165-1584. Available online at: http://dx.doi.org/10.1016/j.sigpro.2011.10.017.

Wu, J. and A. G. Dempster (2010c). "*Code Tracking Variance Analysis for GNSS reciever with "Strobe Correlators"*." IEEE Transactions on Aerospace and Electronic Systems (Accepted on 30/08/2011, in press).

Wu, J., Dempster, A.G. (2008). *Multipath Mitigation Performance Comparison of Strobe Correlators in GNSS Receivers*. International Symposium on GPS/GNSS 2008, Tokyo, Japan. 963-972.

Wu, J., Dempster, A.G. (2011). "*The "BOC-Gated-PRN", A Multipath Mitigation Technique for BOC (n, n) Waveforms.*" IEEE Transactions on Aerospace and Electronic Systems Vol. 47(2): p. 1136-1153.

Yao, Z., M. Lu, et al. "*Unambiguous sine-phased binary offset carrier modulated signal acquisition technique*." Wireless Communications, IEEE Transactions on 9(2): 577-580.

Biography

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